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The Relationship between Electrically Evoked Compound Action Potential and Speech Perception : A Study in Cochlear Implant Users with Short Electrode Array

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Abstract

Objectives—To determine the extent to which electrically evoked compound action potential (ECAP) measurements were related with speech perception performance in implant users with a short electrode array and to investigate the relationship between ECAP measures and performance according to specific devices.

Design—Prospective study.

Setting—Tertiary referral center.

Patients—Seventeen Hybrid cochlear implant users were tested in this study. Subjects were divided into 2 groups: 1) 8 using the Nucleus Hybrid M, 2) 9 using the Nucleus Hybrid RE. In addition, 21 Nucleus Freedom long electrode implant (CI24RE) users were also tested to compare with the results of the old device (CI24M).

Main Outcome measures—ECAP growth functions were recorded using either an interphase gap (IPG) of 8 or 45 us. We then calculated 1) the slope of the growth function, and 2) changes in sensitivity with IPG. For each subject, these measures were compared with performance on tests of word recognition.

Results—The changes in sensitivity using two IPGs showed no correlation with results of word recognition test in Hybrid cochlear implant users. In contrast, relatively strong correlations have been found between the slope of ECAP growth functions and performance on word recognition test. Additionally, when we separate the results of Hybrid M and RE, the slopes of ECAP growth functions from only Hybrid RE CI recipients were significantly correlated with speech performance. The slopes of ECAP growth function in CI24RE users with long electrode were also significantly correlated

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with performance. However, comparing between two independent correlations in RE devices, correlation was higher in Hybrid RE group.

Conclusion—The results presented in this paper support the view that slope of the ECAP growth can show significant correlation to performance with a cochlear implant. Further, these results suggest that the strength of the correlation may be related to the specific device. These results suggest that ECAP measures may be useful in developing a test to predict outcomes with the implant.

Keywords

electrically evoked compound action potential; cochlear implant; Hybrid electrodes

INTRODUCTION

Cochlear implants (CIs) are generally used in individuals with severe to profound hearing loss. Neural survival may be an important factor in determining outcome for this clinical population (1–2). Ever since cochlear implants were first introduced into clinical practice, investigators have looked for physiological and/or psychophysical measures that could be used to predict auditory nerve survival (3–5). Significant correlations between the slope of growth of electrically evoked neural potentials and spiral ganglion cell survival in animals have been reported (3). Recently, Prado-Guitierrez et al. (5) investigated the sensitivity of ECAP (electrically evoked compound action potential) and EABR (electrically evoked auditory brainstem response) to changes in inter-phase gap (IPG) and pulse duration (PD) in deafened guinea pigs. Both electrophysiological measures were found to correlate with nerve survival. Psychophysical measures of threshold and dynamic range in monkeys have also been reported to be associated with the state of the spiral ganglion (4). Despite these positive results with animal subjects, physiological measures, such as the ECAP or the EABR, recorded from human CI users have not proven to be strongly correlated with speech perception (6–8).

Animal studies have typically used single electrode (monopolar) stimulation, which presumably results in a broad pattern of excitation, to measure the ECAP or EABR. Similar measures in human implant users with multielectrode implants typically have shown variations across different electrodes in an individual on growth function measure. Such variations could certainly be an issue in assessing correlations to performance, which is likely dependent on activation at multiple electrode sites within the cochlea, effectively obscuring any correlation. This report describes results of a study in which we revisit that issue in users of the Hybrid (short-electrode) cochlear implant users. Our hypothesis was that with a short electrode array, there would be more uniformity in the response properties across electrodes within an individual. If that is the case, within-subject variations may be smaller than the across-subject differences and consequently physiological measures may better characterize the individual subject.

Thus, the initial goal of this study was to evaluate the relationship between ECAP measurements (amplitude growth and changes in sensitivity with IPG) and speech perception performance in Hybrid implant users. The available subjects included individuals who used both the Nucleus Hybrid RE and Hybrid M cochlear implants. Since the ECAP measurement system in the two devices is different (the Hybrid RE device has a neural telemetry system with a lower noise floor), we hypothesized that the ability to measure ECAP growth at lower response amplitudes might affect our measures of slope of the growth and changes in sensitivity with IPG. Therefore, the relationship between ECAP measures and performance according to specific devices was evaluated. Finally, since we observed differences between the two implant types, we hypothesized that the results in traditional “long” electrode implantees, may also be affected by implant type. We therefore conducted an additional study in which we focused on results obtained from individuals who use a CI24RE cochlear implant with a long (or traditional) electrode array. Using previous data recorded in our laboratory from CI24M users (8), we were then able to compare the relationship between the slope of the ECAP growth function and performance for postlingually deafened adults who use the Nucleus CI24M and CI24RE cochlear implants.

MATERIALS AND METHODS

Nucleus CI24 cochlear implant system

The Nucleus CI24 cochlear implant consists of 22 intracochlear electrodes and two additional extracochlear electrodes. The intracochlear electrodes are numbered 1 to 22, from base to apex. This study shows the results in two types of Nucleus CI24 implant (the Nucleus CI24M and CI24RE (CA)). The Nucleus CI24M implant has a straight electrode array with 22 full platinum bands. In the Nucleus CI24RE device, the 22 perimodiolar intracochlear electrodes are half platinum bands. In addition, the CI24RE is designed for less traumatic cochlear insertion by using the Advance Off Stylet technique (9). Both the CI24M and the CI24RE cochlear implants have neural response telemetry (NRT) capabilities, which allow for direct measurement of the electrically evoked whole nerve action potential from an intracochlear electrode. However, the enhanced NRT capabilities of CI24RE provide a better signal-noise ratio and the ability to detect smaller ECAP responses (10).

Nucleus Hybrid cochlear implant

The Nucleus Hybrid cochlear implant has been designed to provide high frequency information while preserving residual low frequency acoustic hearing (11). At 10 mm long and only 0.2 × 0.4 mm in diameter, its insertion is limited to the lower basal turn of the cochlea. The Hybrid CI has six electrodes spread across an intracochlear array that is shorter and thinner than the electrode array in the traditional Nucleus CI. In this study, two types of Hybrid CIs were used. Hybrid M CI is the hybrid version of the Nucleus CI24M device. Hybrid RE CI is the hybrid version of the Nucleus CI24RE CI. Both devices have a straight electrode array, and the geometry of the electrode contacts is similar.

Subjects

Seventeen postlingually deafened adult subjects, who received a Hybrid CI at the University of Iowa Hospitals and Clinics between 2001 and 2006, participated in study 1. Eight of study participants had Hybrid M CIs, and nine had Hybrid RE CIs. These study participants are identified in the tables and figures using subject numbers determined by the order in which they were implanted. Each subject number begins with either an H-M (Hybrid M) or an H-RE (Hybrid RE). Table 1 shows general demographic data for each study participant.

In study 2, ECAP measures were obtained from twenty-one (24 ears) postlingually deafened adults, who use the Nucleus CI24RE CIs with the 22 intracochlear electrode array. All of these subjects were implanted at the University of Iowa Hospitals and Clinics between 2003 and 2006. Results from these subjects were compared with previous data obtained from 37 individual with Nucleus CI24M CIs and the long intracochlear array (8).

All of the individuals who participated in this study (both short and long electrode CI users) had more than 6 months of experience with their cochlear implant prior to participating in this study. None of the study participants had a history of neurological disorders. Before testing, informed consent was obtained from all individuals.

Behavioral measures

Behavioral dynamic range was measured for each participant to determine the range of stimulus levels to use to record the ECAP growth function. The stimulus used to record the behavioral dynamic range consisted of a continuous train of 25 μs/phase biphasic current pulses presented in a monopolar stimulation mode. In study 1, behavioral measures of threshold (T-level) and maximum comfort level (C-level) were established using an ascending adaptive procedure. For both the Hybrid M and Hybrid RE subjects, two sets of T and C levels were obtained for three intracochlear electrodes (2, 4, and 6), using IPGs of 8 and 45 μs. In study 2, similar estimates of dynamic range were obtained for eight different electrodes (3, 5, 7, 10, 13, 15, 17, and 20) using the 8 μs IPG.

Electrophysiological measures

The ECAP was recorded using either the NRT or Custom Sound EP software from Cochlear Corporation. ECAP responses were obtained using forward masking and a subtraction technique was used to reduce stimulus artifact (12–14).

In study 1, ECAP growth functions were measured on electrodes 2, 4, and 6 of the Hybrid CI using biphasic pulses presented in a monopolar stimulation mode with an IPG of 8 μs and then again using with an IPG of 45 μs. In study 2, ECAP growth functions were recorded from electrodes 3, 5, 7, 10, 13, 15, 17, and 20 of the CI24RE CI with the 8 μs IPG. Regardless of the type of cochlear implant, the time between the masker and probe pulses (masker advance) was fixed at 500 μsec. The morphology of the ECAP response was optimized by adaptively varying the recording parameters for each subject following a protocol outlined by Abbas et al. (12). ECAP growth functions were obtained by fixing the masker at a relatively high stimulation level and systematically varying the probe until no response could be identified. Once a growth function was collected, amplitude of the ECAP was determined offline using custom-designed (MATLAB, V.6.1) software. Standard peak picking techniques were used to assess the difference in amplitude between the negative peak of the ECAP and the following positive peak. ECAP thresholds were determined by the author based on visual inspection of the waveforms and defined to be the lowest probe level eliciting a waveform.

Two response parameters were extracted from the ECAP growth measures. Initially, linear regression techniques were applied to the ECAP growth data and slope of the best fit regression line (in μV/CL) was calculated. The second metric was the change in sensitivity (the change in current level required to record ECAPs with the same amplitude) between the 8 μs IPG and 45 μs IPG growth functions. Figure 1 shows example growth functions for the two IPGs (implant recipient H-RE5). These functions are typical in that they are approximately parallel but there is a shift in sensitivity with a lower threshold for the 45 μs IPG condition. In order to quantify the difference between these two functions, ECAP amplitude was normalized to that obtained in response to the maximum amplitude recorded using the 8 μs IPG. We estimated the magnitude of this shift by calculating the mean difference in stimulation level for criterion normalized amplitudes of 0.2, 0.4, 0.6, and 0.8, indicated in the figure as indicated by the horizontal lines. This gave us a single measure of effect of changing IPG.

In study 1, we used these three electrophysiological measures to assess correlations to word recognition scores in Hybrid CI users. The correlations to performance were calculated relative to the average of 3 electrodes for each measure. In study 2, which focused on individuals who use the traditional length CI, the average slope of the ECAP growth functions for the 8 electrodes was compared with performance using the device.

Speech measures

Speech perception in quiet was assessed using the Consonant-Nucleus-Consonant (CNC) Monosyllabic Word Test (15). This test was administered in quiet with the speech signal presented at 70 dB SPL in the sound field. Results are reported in percent of the total number of words correct. Speech perception in noise was assessed using Bamford-Kowal-Bench Speech-in-Noise (BKB-SIN) test (16–17). BKB sentences were presented at 65 dB SPL in four-talker babble. The level of the speech signal was fixed. The level of the noise was changed in 3 dB increments. Performance was assessed for signal-to-noise ratios (SNR) ranging from 21 dB to −6 dB. Results of the BKB-SIN test are the mean SNR that yielded a score of 50% correct on target words in the sentence. For both tests, the speech is presented from a single, front facing loudspeaker at 1 meter distance from the subject. For the BKB SIN test, the noise is also presented from the same loudspeaker as the speech.

Both ipsilateral and contralateral ear canals were occluded during the test procedure to insure that the responses reflected performance with the CI alone rather than a combination of electric and acoustic hearing.

RESULTS

Study 1 : Relationship between ECAP and Speech Perception in Hybrid Cochlear Implant Users

The primary goal of this study was to determine whether ECAP measures might be correlated with performance in Hybrid CI users. Figure 2 shows ECAP growth functions recorded from electrode 4 using the 8 μs IPG for all 17 study participants. The panel on the left shows data obtained from Hybrid RE users. The panel on the right shows similar growth functions obtained from Hybrid M CI users. ECAP threshold was defined as the current level required to evoke a peak to peak amplitude of >5 μV for Hybrid RE, and >20 μV for Hybrid M. This difference was due to differences in the noise floor between devices. The slope of each growth function in μV/CL is indicated in parentheses to the right of each subject number in the legend.

In order to compare slope of the ECAP growth functions with performance, we averaged the slope measures from 3 electrodes for each Hybrid implant user. Figure 3 shows these averaged slopes plotted as function of the speech perception scores for individual study participants. The figure on the left shows results obtained from 17 individuals and compares average slope of the ECAP growth function with speech understanding measured in quiet using CNC words. The panel on the right shows similar data from 15 Hybrid CI users comparing slope of the ECAP growth functions with speech understanding in noise measured using the BKB-SIN test as more difficult test. When the data from both Hybrid M and Hybrid RE cochlear implant users are combined, linear regression analysis revealed that there is a significant correlation between the slopes of ECAP growth functions and performance on both CNC words list ($r=0.58$, $p<0.05$) and the BKB-SIN test ($r=-0.53$, $p<0.05$). Given the positive correlations between slope of the ECAP growth functions and performance with the Hybrid CI, we were interested in exploring effect of device type. Figure 3 shows the data to allow comparison of results obtained from Hybrid M and Hybrid RE CI users. In both plots, open circles are used to represent ECAP data recorded from Hybrid M CI users, and filled circles are used to represent ECAP data recorded from Hybrid RE CI users. For both speech perception measures, only the slopes of ECAP growth functions from Hybrid RE CI recipients were significantly correlated with speech performance (CNC: $r=0.90$, $p<0.01$; BKB-SIN: $r=-0.79$, $p<0.05$). In addition, we also compared slope of the ECAP growth functions with the amount of residual hearing by preoperative pure tone average (Table 1). However, there was no correlation between them ($r=-0.04$, $p>0.05$).

Figure 4 shows speech perception scores plotted as a function of the change in sensitivity with IPG. The figure on the left shows results obtained from 17 individuals and compares the change in sensitivity with IPG with speech understanding measured using CNC words. The figure on the right shows similar data from 15 hybrid CI users comparing the change in sensitivity with IPG with speech understanding in noise measured using the BKB-SIN test. No significant correlations between the changes in sensitivity using two IPGs and both speech perception scores were revealed (CNC: $r=0.02$, $p > 0.05$; BKB-SIN: $r=-0.02$, $p > 0.05$). The result obtained from Hybrid M or Hybrid RE CI users also shows no significant correlation (data not shown).

Study 2 : Relationship between ECAP and Speech Perception in Standard cochlear implant users

We hypothesized that the significant correlations between ECAP growth and performance shown in Fig 3 could have resulted from two factors: the fact that the Hybrid RE CI device has fewer stimulating electrodes and/or that it has an “improved” neural telemetry system. We therefore proceeded to make measurements of slope of the ECAP growth function in individuals with the Nucleus CI24RE device but with the standard, “long” electrode and compared those data with those reported in a previous study using the standard CI24M implant (8). In this case, the measures are limited to CNC word scores. The panel on the left in Figure 5 plots the CNC word scores as a function of the slope of the ECAP growth functions for 24 ears with the standard CI24RE implants. The panel on the right shows results obtained from 37 Nucleus CI24M CI users from a previous study (8). Interestingly, the slopes of ECAP growth function from data in CI24RE users were 3.63±1.72 μV/CL, whereas those from data in CI24M users were 8.99±4.38 μV/CL. That is, the slopes in CI24RE users were lower than those in CI24M users. As shown in Figure 5, data from CI24M implant users did not show a significant relationship between the slope of the ECAP growth function and CNC word scores. In contrast, a weak but significant correlation between the slope of the ECAP growth function and CNC word scores ($r=0.47$, $p<0.05$) was found in CI24RE CI users.

Finally, we compared the results of Hybrid RE with those of CI24 RE to test the hypothesis that with a short electrode array, physiological measures may better characterize the individual subject performance. Pearson’s correlations for the Hybrid RE group (n=9) and the CI24RE group (n=24) were 0.90 and 0.47, respectively. We performed a comparison between two independent correlations to examine whether there is a difference between two correlations. The statistical analysis was conducted by a correlation comparison test with statistical significance set at a p value of 0.05. A comparison between two independent correlations showed a significant difference ($p<0.05$). Therefore, the Hybrid RE group with short electrode had a better correlation than the CI24RE group with the long electrode.

DISCUSSION

One of the primary goals of this study was to determine the extent to which ECAP measurements were related to speech perception performance in implant users. Since performance with CI is negatively correlated with an individual’s duration of deafness prior to implantation, neural survival may be an important factor in determining outcome (1–2,18). However, to date, the human studies relating physiological measures such as the threshold and growth of the ECAP and EABR have not shown clear relationships to speech perception abilities (6–8), despite of the positive results in which these measures were correlated with nerve survival in animals (3,19–20).

We evaluated these correlations in Hybrid CI users under the hypothesis that, with a short electrode array, there would be more uniformity in the response properties across electrodes within an individual. In that way, the within-subject variations may be smaller than the across-subject differences and consequently physiological measures may better characterize the individual subject. Average data across electrodes in standard (long-electrode) CI may not show any clear relationship with performance due to non-uniform neural survival in the cochlea and difference in the electrical interface at the active electrode contacts (21–22). Therefore, we examined ECAP measurements, such as amplitude growth and changes in sensitivity with IPG, in Hybrid CI users to explore the relationship with performance.

The results show that the slopes of the ECAP amplitude intensity functions are significantly correlated with performance on both CNC words and BKB-SIN test. In both cases, ECAP growth functions with steeper slopes were correlated with better performance. These findings are generally consistent with our hypothesis, and are in contrast to other studies using CI users with long electrode for either ECAP or EABR (6–8). In contrast, the changes in sensitivity with IPG show poor correlation with results of speech performance (see Figure 4). These results do not support our hypothesis. Previous studies in guinea pigs (5) demonstrated correlation of similar measures with nerve survival. Differences between these studies and ours may be attributed to species differences or differences in measurement sensitivity. More likely however, other factors that affect performance on speech perception tests, in addition to degree of nerve survival, may increase the variance in our measures and reduce the correlations evident in this study.

The second goal of this study was to determine whether there were differences between the old and new devices (M vs RE). We measured the slope of the ECAP growth functions in short and long electrode CI users and examined the relationship between these measures and performance. Our hypothesis was that a stronger correlation between the slope of the ECAP growth functions and performance would be found in the new device (RE) because the newer CI has a neural response telemetry system with a lower noise floor and consequently might produce more accurate measures of growth at low levels.

The data presented in Figure 3 and 5 are generally consistent with that hypothesis. As is shown in Figure 3, the slopes of growth functions in only Hybrid RE CI users are correlated with speech performance when we separate the results of Hybrid M and RE. Figure 5 also shows that the slopes of growth functions in CI24RE CI users are positively correlated with speech perception scores whereas no significant correlation was found for CI24M users (8). These results may be due to the improved design of the CI24RE amplifier which allows to obtain measurement responses at lower current levels (10,23).

The improved correlation between performance and the slopes of ECAP growth functions for the RE implant users compared to M implant users is most likely due to the differences in the NRT system but there are also other differences among the different implants used in this study. Probably the most relevant are the differences in the electrode array. For the long electrode arrays, the CI24M has the initial straight array conforms to cochlea, presumably by following the path of scala tympani. It is generally assumed that the straight array of the CI24M is usually positioned near the outer wall of the cochlea. The CI24RE implant users all have the Contour array that has half-banded electrodes (facing the modiolus) and also a curved array that is generally assumed to be placed closer to the inner wall of the scala tympani and consequently closer to the stimulable neurons (24–25). In addition, the Advance Off Stylet technique used to insert the 24RE array may allow for better preservation of auditory neurons (9,21). Gordin et al. (21) also reported that ECAP thresholds for the CI24RE device were significantly lower as compared with those of CI24M. The electrode placement closer to stimulable neurons could result in lower thresholds and more gradual growth of response with stimulus level, consistent with slope data in Figure 5. For both Hybrid implants, the electrodes arrays are similar straight arrays, but the NRT system is different, that is, the RE implant – either hybrid or full array – utilizes the improved recording system effectively has a lower noise floor. We suggest here that the lower noise floor, resulting in the ability to make ECAP measures at lower response

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amplitudes may improve the correlations to performance. ECAP measures with a lower noise amplifier provide more accurate assessment of slope but also provide measures at lower levels which may be more indicative of nerve fiber density near the stimulating electrode and therefore may provide a more accurate assessment of nerve survival.

Finally, it is of interest to compare the results of Hybrid RE with those of CI24 RE. The correlation between performance and the slope of the growth functions in Hybrid RE CI users was statistically stronger than the correlation obtained in CI24RE CI recipients. We hypothesized initially that improved correlations may result for Hybrid CI users since, with fewer electrodes, the variation in response across electrodes may be reduced. Thus, that result suggests that, with a short electrode array, physiological measure may better characterize the individual subject.

As noted above, the data with M vs RE suggest that the internal recording system may be an important factor. Nevertheless, a comparison of 24RE vs Hybrid RE correlations, showing improved correlation with the Hybrid, suggests that the limited electrodes may also be a factor as originally hypothesized.

To date, electrophysiologic measures have been reported to be helpful in the process of fitting the CI to an individual (26–27), as well as in diagnosing and managing CI failure (28–29). In addition, our results show that ECAP measures may also be useful in developing a test to predict outcomes with the implant. This clearly requires further testing. It is possible that a within subjects test, using the full array as well as a more limited set of electrodes could more directly address this issue.

CONCLUSION

This work describes the extent to which ECAP measurements are related with speech perception performance in short electrode implant users. The slope of ECAP growth functions in Hybrid CI recipients was significantly correlated with speech performance on tests of word recognition. In addition, the positive correlation may be also related to the device. Since the effectiveness of cochlear implants can be quite variable, these results show that ECAP measures may be useful in developing a test to predict outcomes with the implant.

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REFERENCES

1. Otte J, Schunknecht HF, Kerr AG. Ganglion cell populations in normal and pathological human cochleae. Implications for cochlear implantation. Laryngoscope 1978;88:1231–1246. [PubMed: 672357]
2. Nadol JB, Young YS, Glynn RJ. Survival of spiral ganglion cells in profound sensorineural hearing loss: implications for cochlear implantation. Ann Otol Rhinol Laryngol 1989;98:411–416. [PubMed: 2729822]
3. Smith L, Simmons FB. Estimating eighth nerve survival by electrical stimulation. Ann Otol Rhinol Laryngol 1983;92:19–23. [PubMed: 6824273]
4. Pfingst BE, Sutton D, Miller JM, Bohne BA. Relation of psychophysical data to histopathology in monkeys with cochlear implants. Acta Otolaryngol 1981;92:1–13. [PubMed: 6895572]

5. Prado-Guitierrez P, Fewster LM, Heasman JM, McKay CM, Shepherd RK. Effect of interphase gap and pulse duration on electrically evoked potentials is correlated with auditory nerve survival. Hear Res 2006;215:47–55. [PubMed: 16644157]
6. Abbas PJ, Brown CJ. Electrically evoked auditory brainstem response: growth of response with current level. Hear Res 1991;51:123–137. [PubMed: 2013539]
7. Brown CJ, Abbas PJ, Bertschy M, et al. Longitudinal assessment of physiological and psychophysical measures in cochlear implant users. Ear Hear 1995;16:439–449. [PubMed: 8654899]
8. Brown, CJ.; Abbas, PJ.; Hughes, M.; Tyler, R.; Parkinson, A. Cross-electrode differences in EAP growth and recovery functions measured using the Nucleus NRT software: correlation with speech performance. Presented at the Conference on Implantable Auditory Prostheses; Ailoma, CA. 1999.
9. Roland JT. A model for cochlear implant electrode insertion and force evaluation: results with a new electrode design and insertion. Laryngoscope 2005;115:1325–1339. [PubMed: 16094101]
10. Patrick JF, Busby PA, Gibson PJ. The development of the Nucleus Freedom Cochlear implant system. Trends Amplif 2006;10:175–200. [PubMed: 17172547]
11. Gantz BJ, Turner CW. Combining acoustic and electrical hearing. Laryngoscope 2003;113:1726–1730. [PubMed: 14520097]
12. Abbas PJ, Brown CJ, Shallop JK, et al. Summary of results using the Nucleus CI24M implant to record the electrically evoked compound action potential. Ear Hear 1999;20:45–59. [PubMed: 10037065]
13. Brown CJ, Abbas PJ, Gantz BJ. Preliminary experience with neural response telemetry in the Nucleus CI24M cochlear implant. Am J Otol 1998;19:320–327. [PubMed: 9596182]
14. Brown CJ, Hughes ML, Luk B, Abbas PJ, Wolaver AA, Gervais JP. The relationship between EAP and EABR thresholds and levels used to program the Nucleus 24 speech processor: Data from adults. Ear Hear 2000;21:151–163. [PubMed: 10777022]
15. Peterson FE, Lehiste I. Revised CNC lists for auditory tests. J Speech Hear Disord 1962;27:62–70. [PubMed: 14485785]
16. Etymotic Research. BKB-SIN Speech-in-Noise Test, Version 1.03 (Compact Disk). Elk Grove Village, IL 60007: Etymotic Research, 61 Martin Lane; 2005.
17. Bench J, Kowal A, Bamford J. The BKB (Bamford-Kowal-Bench) sentences lists for partially hearing children. Br J Audiol 1979;13:108–112. [PubMed: 486816]
18. Gantz BJ, Tyler RS, Knutson JF, et al. Evaluation of five different cochlear implant designs: audiologic assessment and predictors of performance. Laryngoscope 1988;98:1100–1106. [PubMed: 3172957]
19. Hall RD. Estimation of surviving spiral ganglion cells in the deaf rat using the electrically evoked auditory brainstem response. Hear Res 1990;45:123–136. [PubMed: 2345111]
20. Miller CA, Abbas PJ, Robinson BK. The use of long-duration current pulses to assess nerve survival. Hear Res 1994;78:11–26. [PubMed: 7961173]
21. Gordin A, Papsin B, James A, Gordon K. Evolution of cochlear implant arrays result in changes in behavioral and physiological responses in children. Otol Neurotol. 2010 (in press).
22. Hughes ML, Abbas PJ. Electrophysiologic channel interaction, electrode pitch ranking, and behavioral threshold in straight versus perimodiolar cochlear implant electrode arrays. J Acoust Soc Am 2006;119:1538–1547. [PubMed: 16583899]
23. van Dijk B, Botros AM, Battmer RD, et al. Clinical results of AutoNRT, a completely automatic ECAP recording system for cochlear implants. Ear Hear 2007;28:558–570. [PubMed: 17609616]
24. Tykocinski M, Saunders E, Cohen LT, Treaba C, Briggs RJS. The Contour electrode array: safety study and initial patient trials of a new perimodiolar design. Otol Neurotol 2001;22:33–41. [PubMed: 11314713]
25. Saunders E, Cohen L, Aschendorff A, et al. Threshold, comfortable level, and impedance changes as a function of electrode-modiolar distance. Ear Hear 2002;23:28S–40S. [PubMed: 11883764]
26. Brown CJ, Abbas PJ, Fryauf-Bertschy H, Kelsay D, Gantz BJ. Intraoperative and postoperative electrically evoked auditory brain stem responses in Nucleus cochlear implant users: Implications for the fitting process. Ear Hear 1994;15:168–176. [PubMed: 8020649]

27. Shallop JK, VanDyke L, Goin DW, Mischke RE. Prediction of behavioral threshold and comfort values for Nucleus 22-channel implant patients from electrica auditory brain stem response test results. Ann Otol Rhinol Laryngol 1991;100:896–898. [PubMed: 1746823]
28. Mahoney MJ, Proctor LAR. The use of averaged electrode voltages to assess the function of Nucleus internal cochlear implant devices in children. Ear Hear 1994;15:177–183. [PubMed: 8020650]
29. Hughes ML, Brown CJ, Abbas PJ. Sensitivity and specificity of averaged electrode voltage measures in cochlear implant recipients. Ear Hear 2004;25:431–446. [PubMed: 15599191]

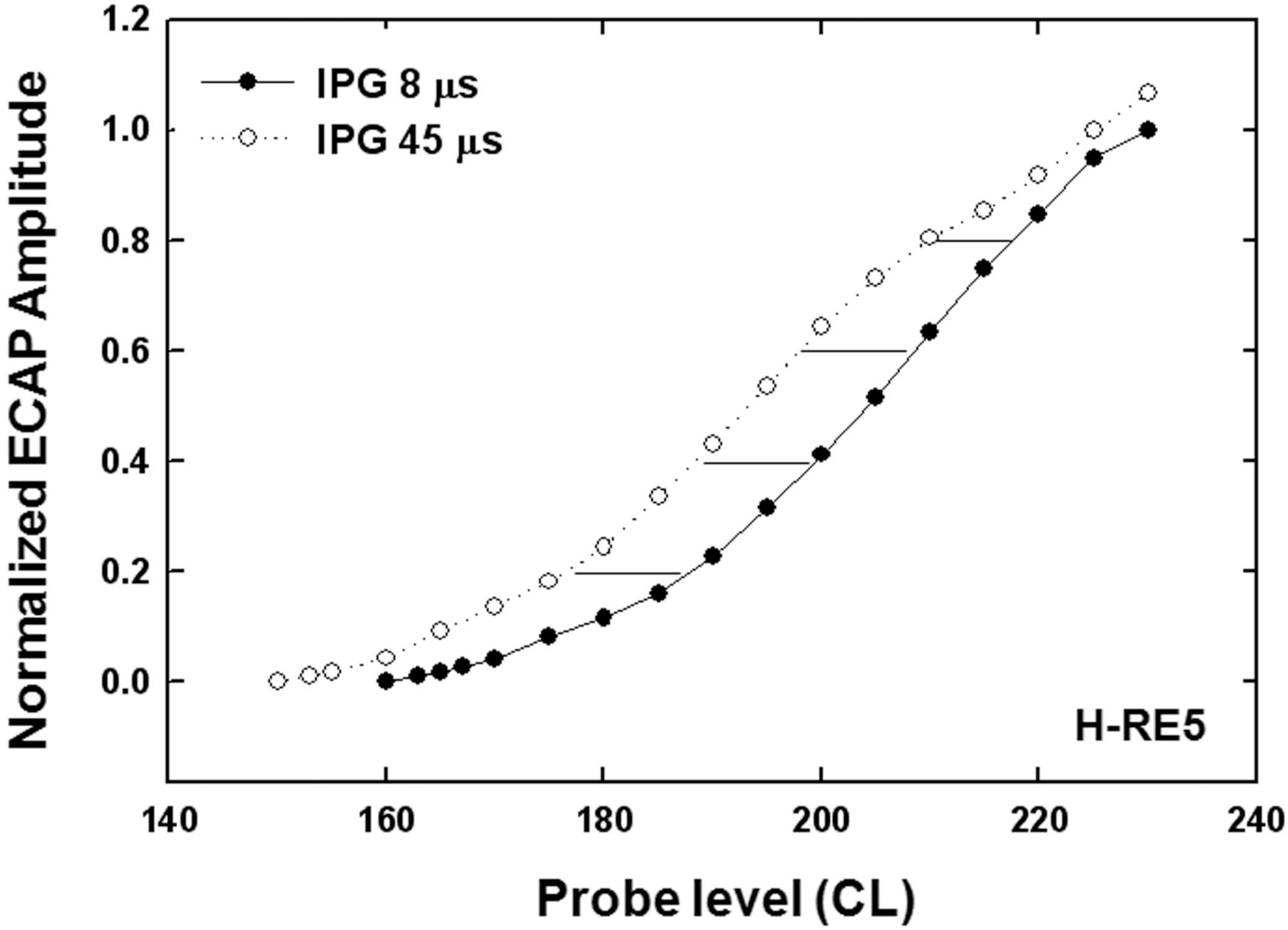

Figure 1.

The change in sensitivity of the ECAP using two IPGs of 8 and 45 µs is shown from a single implant recipient (H-RE5) in response to stimulation on electrode 2. The change in sensitivity was defined as current change needed to equalize ECAP amplitude when IPG was increased from 8 to 45 µs. ECAP amplitudes were normalized to the largest amplitude of the 8 µs IPG growth function. The measures of shift in sensitivity at 0.2, 0.4, 0.6, and 0.8 normalized amplitude were used to calculate the mean change in sensitivity.

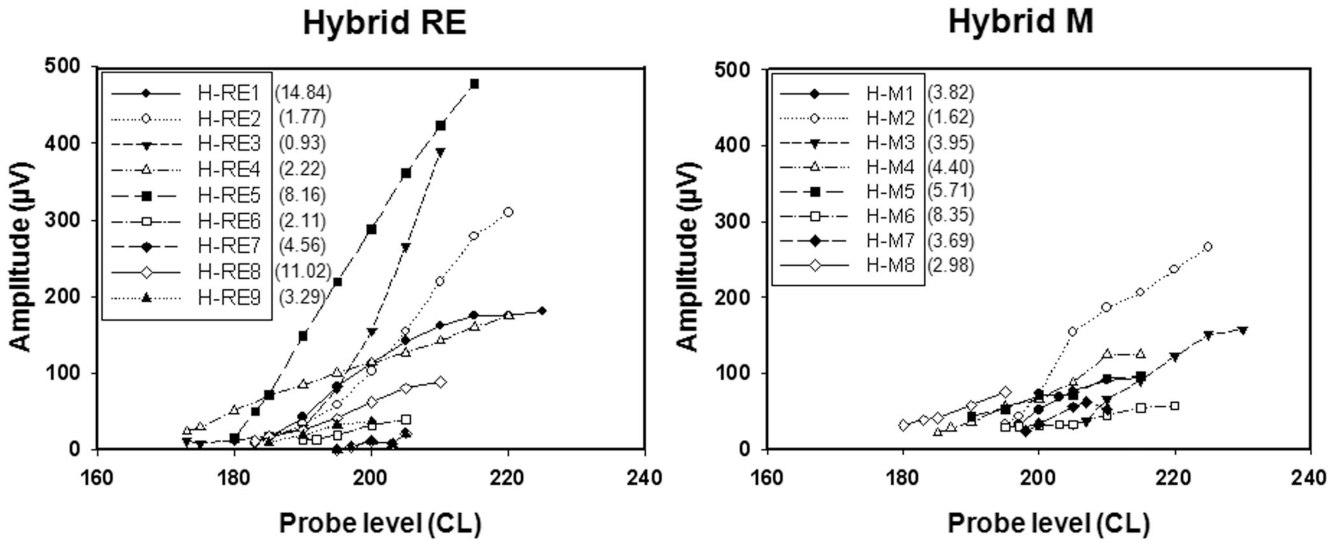

Figure 2.

The growth functions using 8 μs IPG of electrode 4 measured from the 17 subjects. The left column shows the Hybrid RE growth functions and the right panel shows the Hybrid M growth functions. The slope of growth function was calculated using linear regression. The slope of each growth function in μV/CL is indicated in parentheses to the right of each subject number in the legend.

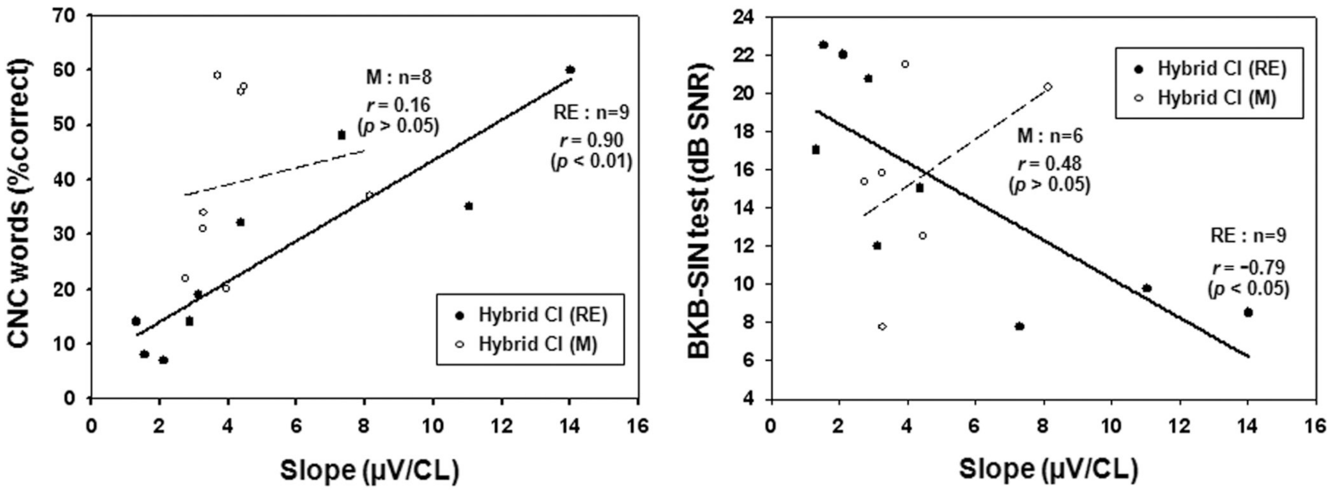

Figure 3.

The relationship between the slopes of the ECAP amplitude intensity functions and the speech perception scores is shown for subjects with Hybrid RE and M CI. Left and right columns show correlations between slope of growth function and speech understanding in quiet (CNC words), and noise (BKB-SIN test), respectively. Open circles represent Hybrid M, and filled circles indicate Hybrid RE. Only Hybrid RE CI recipients show a significant correlation between the slope of the ECAP growth function and speech performance_(Left column : r=0.90, p<0.01 ; Right column : r=−0.79, p<0.05).

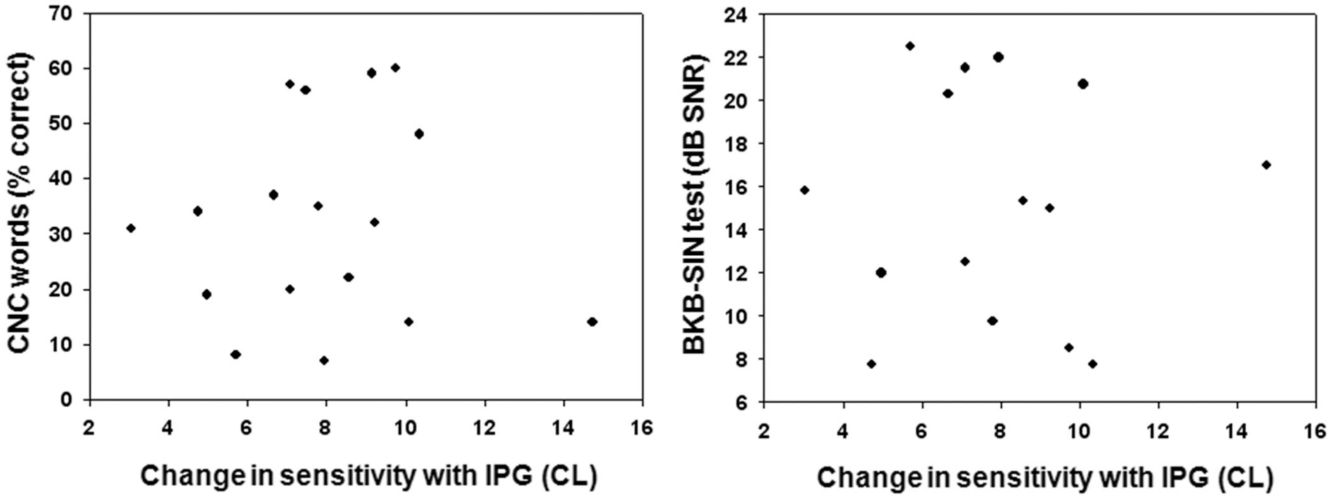

Figure 4.
The changes in sensitivity with two IPGs obtained for subjects with Hybrid CIs are plotted as function of the scores of CNC words (Left column) and the scores of BKB-SIN test (Right column). This measure showed no correlation with results of speech performance (CNC test: $r=0.02$, $p > 0.05$; BKB-SIN test: $r=-0.02$, $p > 0.05$).

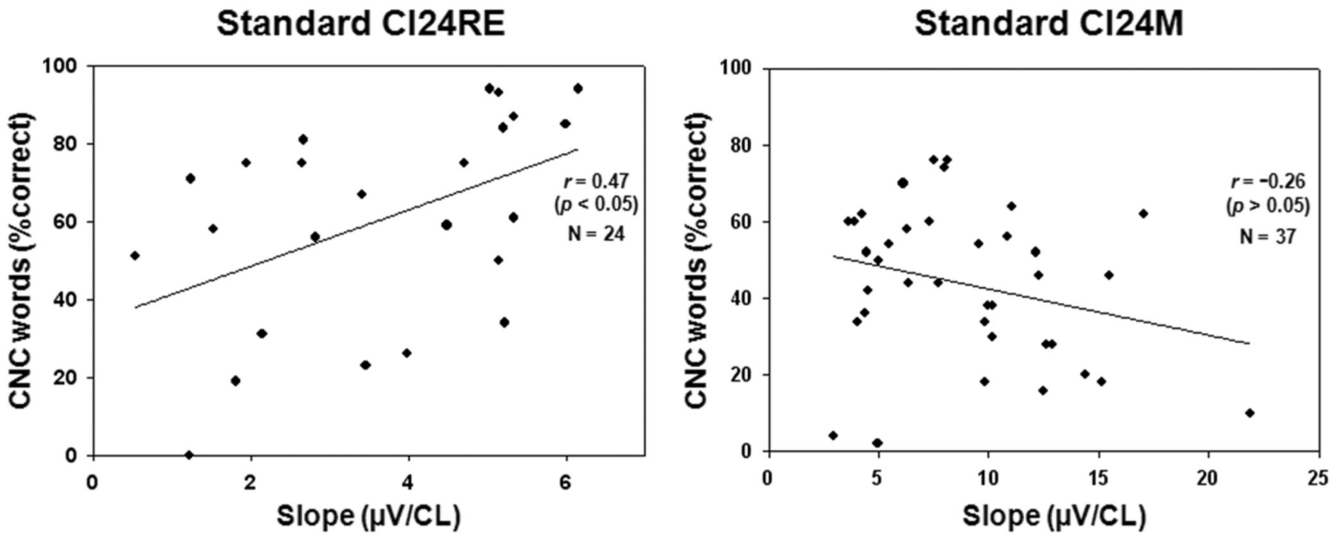

Figure 5.

The relationship between the slope of the growth function and performance is shown for CI24M and CI24RE CI recipients. The left column plots the CNC word scores as a function of the slopes of the ECAP growth functions for 24 ears with CI24RE implants. The right column plots data from 37 CI24M CI recipients (Brown et al., 1999). In contrast to CI24M users, CI24RE recipients show a significant correlation between the slope of the ECAP growth function and CNC word scores ($r=0.47$, $p<0.05$).

Table 1

General demographic information on seventeen study participants with Hybrid CI, including gender, age at time of testing, etiology of hearing loss (when known), preoperative PTA, ear implanted, type of implant, and duration of CI use at the time of testing.

Subject	Gender	Age (yr)	Etiology	Preoperative PTA* (dB)	Ear implanted	Type of implant	Duration of CI** use (Mo)
H-M1	F	39	Unknown	103	R	Hybrid M	83
H-M2	M	57	Unknown	93	L	M	76
H-M3	F	62	Autoimmune	105	L	M	65
H-M4	M	69	Unknown	108	R	M	58
H-M5	M	73	Unknown	99	L	M	49
H-M6	F	69	Unknown	104	R	M	47
H-M7	F	69	Unknown	99	L	M	45
H-M8	M	50	Unknown	101	R	M	39
H-RE1	F	57	Unknown	99	R	Hybrid RE	31
H-RE2	F	62	Unknown	89	L	RE	30
H-RE3	F	52	Autoimmune	86	R	RE	28
H-RE4	M	76	Familiar	109	L	RE	27
H-RE5	M	51	Unknown	96	R	RE	23
H-RE6	F	52	Unknown	98	L	RE	17
H-RE7	F	82	Unknown	108	R	RE	16
H-RE8	M	65	Noise exposure	91	L	RE	15
H-RE9	F	54	Unknown	95	L	RE	13

* PTA, pure tone average of 1, 2, 4, 8kHz
(No responses at 2, 4kHz were converted to 120dB. No response at 8kHz was converted to 95dB)

** CI, cochlear implant